The influence of system design-related factors on the safety performance of metro drivers

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Abstract

Although it is accepted that system design affects train driver performance, the literature related to this phenomenon - in relation to urban railways and metro systems in particular - is scarce. Metro systems differ significantly from mainline railways, being closed systems, with shorter headways, a greater number of stations and more signals encountered. This paper aims to investigate the effects of design-related performance shaping factors on metro driver performance, by analysing historical incident records for the 2011-13 period on the Tyne & Wear (T&W) Metro (UK). Bivariate statistical analysis has been used, to assess the potential inter-dependency of the performance shaping factors and other common causal factors, for various driver-related incident types. In addition to category A Signals Passed at Danger incidents (SPaDs), station overruns, and incidents associated with station procedures have also been assessed. The results show the significant importance of the location (design) based performance shaping factors in incident propagation mechanisms in the Metro. The two years under investigation display increased consistency between driver-related incidents and locations, rather than time of day, or season. In addition, the highest correlation between incidents has been found in terms of locations. Deviations from a standardised T&W Metro station design were found to associate with either an increase or decrease in incident rates, depending on whether additional complexity or simplicity was introduced. Although the features of metro systems suggest improved route knowledge and system familiarity among drivers, the results show that this can actually lead to an unsatisfactory safety-related performance during non-routine operations, e.g. engineering works, or driving in sidings.

Keywords

Urban rail, metro systems, safety, system design, human factors, performance shaping factors, human performance.

Introduction

Railway systems are one of the safest modes of transport, but they are not risk-free; incidents do occur, in a range of magnitude, and sometimes with severe consequences. Despite being the European safety leader in railway industry, United Kingdom still sees hundreds of major passenger and workforce incidents annually (1). Even the incidents receiving the most of attention since the beginning of the 21st century, signals passed at danger (SPaDs), still occur in numbers. According to (1) 2014/15 saw 299 SPaDs in the UK, including Tyne & Wear Metro system. Looking closer into the T&W Metro's contribution to this statistics it can be seen that its proportion of such incidents is significantly higher than the proportion of the passenger journeys in the UK (approximately 4% and 2.3% respectively). Of course, this situation is a result of the metrics not accounting for the number of encountered signals and stations stops but there is also a significant gap in the research of metro systems. Furthermore, due to the number of station stops in T&W Metro platform-train interface (PTI) incidents have additional risks associated with those but research in this area is scarce.

Despite the technological advances of modern systems, a typical railway still depends on the safety-related performance of front line staff, especially drivers. Egea et al (2) found out that that approximately 80% of the risk in the railway industry can be attributed to front line staff, whereas most investment is streamed into the technical domain. Human Factors (HF) is considered a suitable approach to address all aspects of safety, in safety-critical industries and systems (3). The increasing relevance of this discipline is evidenced by the increased involvement of human factor specialists in the design of railway systems (4).

Understanding performance shaping factors (PSFs) can help create safety-critical systems that include a human operator as an asset, rather than a risk carrier. Blackman, Gertman (5) describe a PSF as "an aspect of the human's individual characteristics, environment, organization, or task that specifically decrements or improves human performance". In other words, PSFs are factors that have an effect on the likelihood of human error. One of the most significant characteristics of using PSFs, is the recognition that human error is caused by a mix of different factors, thus acknowledging inter-dependence (6). Progress in this research area will potentially provide a means to estimate a holistic response to any design alterations in the system. Previous research has highlighted the importance of system design-related factors to driver performance, as well as recognising that the operation of railways includes a variety of human factors (7).

This paper explores the influence of system design-related aspects on safety performance and incident propagation in metro systems, from both the HF and PSFs perspectives, applied to the particular case of the Tyne & Wear Metro system in the United Kingdom (UK), using a bivariate statistical analysis of driver-related incidents between 2011 and 2013.

This paper presents a comprehensive assessment of the rail human factors current body of knowledge, as related to driver performance, followed by a brief overview of the design and operational characteristics of the T&W Metro. Further sections of the paper introduce the research methodology used, prior to presenting the results. Finally, these results are discussed and summarised in the conclusions.

Rail human factors

Despite the advancement of rail human factors, there is no holistic understanding of the influence of design-related PSFs on train driver performance. Existing research appears to be fragmented and is usually focused on a single design aspect of a railway system. Several studies have looked at various parts of the railway system design, rather than the whole. For instance, the effects of low frequency noise in the cab environment, inducing stress, fatigue, depression and errors of judgement, has been studied (8-11). The inter-dependency of tilt angle in tilting trains, and various anthropometric parameters of passengers in motion sickness propagation, have been reported by Beard and Griffin (12). Similarly, the relationship between user-centred cab component design, and driver workload and performance, has been explored by Hitchcock, Morris (13), Sumpor, Tos (14) and Van Der Weide, Frieling (15). Research on driver-machine interaction and cab-signalling has been conducted with a focus on driver workload and situational awareness (16-18). Signal sighting, and infrastructure design, have been explored from the human factors perspective (19-22). The UK's Network Rail has produced internal policies to increase the integration of human factors into areas such as signalling design, human-machine interaction, and others (23). The phenomenon of Signal Passed at Danger has been studied from the human factors perspective, where research has attempted to analyse and understand patterns of SPaD incident propagation (24). In addition, various tools have been created for accident investigators, to help determine causal factors in SPaDs (25). For instance, the UK's Rail Safety and Standards Board (RSSB) released a guide for the industry to support the understanding of human factors in the rail environment (26). A significant part of this guide is focused on the design of the immediate physical environment of the driver, including equipment and workplace design. It is acknowledged by the industry that successful system design can mitigate adverse environmental effects that significantly undermine driver performance (27). Concentrating on human factors early in the design stages helps eliminate a substantial amount of risk, by reducing the number of human/system-related clashes (4).

To the authors' knowledge there is no specific literature available focusing on metro systems from the HF and PSF perspectives. Metro systems differ from mainline railways in ways that might significantly change incident propagation processes. A typical metro is a closed system that is smaller than mainline railway systems. The variability of infrastructure, rolling stock and routes is also significantly reduced in metro systems. Therefore, metro drivers generally follow identical routes, in identical rolling stock, on every shift, which enhances route knowledge. According to Naweed (28), route knowledge is one of the most important driver skills, as a considerable amount of moving authority is often hidden from a driver's view. Furthermore, in terms of training, the smaller variability in encountered scenarios means faster and more thorough route learning (28). In addition, urban railways are high capacity systems with short headways and shorter distances between stations. Consequently, metro drivers not only encounter more station stops, but also more signals. This, together with the use of highly effective brakes combined with Automatic Train Protection (ATP), creates a risk profile which differs from that of mainline railways.

The Tyne & Wear Metro system

The Tyne & Wear Metro is located in the Tyne & Wear conurbation that connects Newcastle upon Tyne, Gateshead, South Tyneside, North Tyneside and Sunderland. It first opened in 1980 and mostly adapted existing heavy rail infrastructure. Today the system spans more than 78 km and has 60 stations. A map of the Metro can be seen in figure 1. The fleet consists of 45 two-car train sets. The Metro uses the original class 994 rolling stock, which is currently undergoing its ¾ life refurbishment. The cab layout is similar to the original, albeit with some improvements and additions, such as a modernised driver seat and advisory system. The system has two routes; the South Gosforth to Pelaw section of the network is considered the “core” of the system, as both routes pass through it, and thus it has the highest daily throughput of trains.

The majority of the stations in the T&W Metro system are located overground. There are only eight underground stations in the network (St James, Monument, Manors, Jesmond, Haymarket, Central, Gateshead, Sunderland). However, the Metro’s own classification counts built-over (subsurface) stations, such as Regent Centre, as underground stations. Using the Metro’s own classification method, thirteen stations in the system can be considered underground (the previous nine plus North Shields, Four Lane Ends, Regent Centre, Heworth). Most of the stations have two platforms with a length suitable for two-car train sets. The underground stations, the “legacy” stations adapted from the older heavy rail system, and some other stations, e.g. Pelaw, have longer platforms. There are twelve line and service terminus stations in the Metro. Line terminuses (Airport, St James, South Shields and South Hylton) have either a single platform, or a layout allowing trains to arrive at any of the two available platforms. The service terminuses are used for short services and have turn-back facilities at a station, or in sidings.

The majority of the stations fall into one of the three types of standard designs used in the Metro (figure 2). Type 1 stations are overground stations and some subsurface stations. Type 2 stations are only overground stations, whereas type 3 designs can be seen only at the Newcastle and Sunderland city centre underground stations. All of these design types include driver only operation (DOO) dispatch equipment (a mirror or a monitor), platforms, and a running signal. Instead of the stopping position markers, Type 3 stations include a small sign on a wall next to the monitors to advise drivers of the best stopping point. Despite a high level of standardisation, some of the stations deviate from these designs. For example, Tynemouth would be considered Type 1, but the running signal is on the opposite side of the track, whereas Cullercoats (also Type 1) has no running signal at all. Another design aspect that tends to change from station to station, is the point at which passengers enter onto the platform.

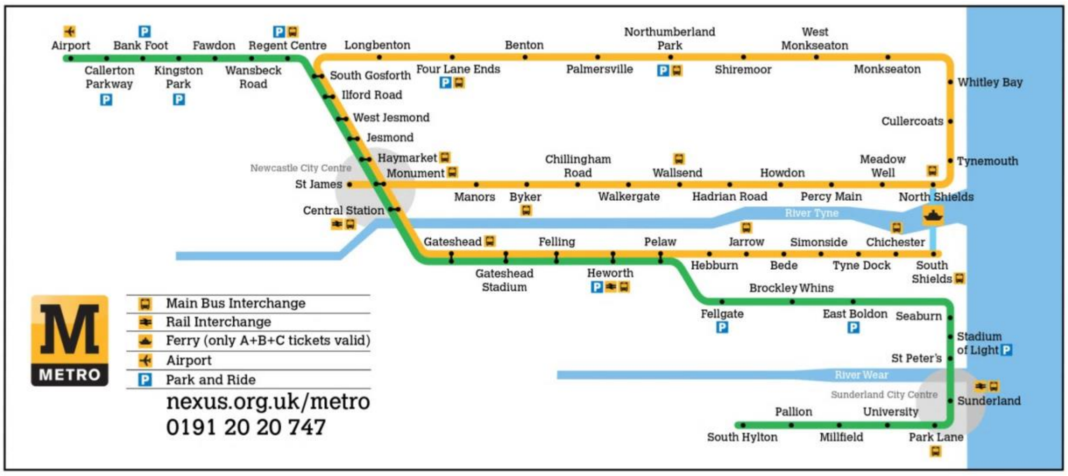

Figure 1. Map of the Tyne & Wear Metro.

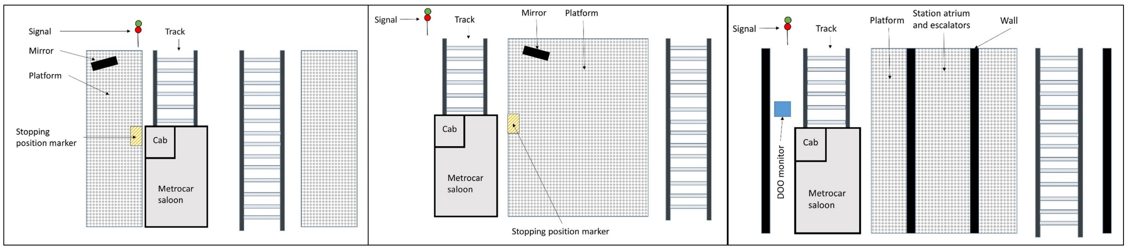

Figure 2. Three main layouts of T&W Metro stations. From left to right: Type 1, Type 2 and Type 3.

The Tyne & Wear Metro operates on its own infrastructure, as well as some sections using track shared with Network Rail infrastructure; thus there is a variety of signalling used. Most of the system has simple two-aspect signalling, with occasional fixed distants and three-aspect signals. However, the Pelaw to Sunderland route uses Network Rail infrastructure and consequently utilises standard mainline four-aspect signalling, with yellow and double yellow signals. The Pelaw – Sunderland route section is shared with both passenger and freight mainline trains, which operate at various speeds. The Gateshead Stadium – Pelaw section runs parallel to the Network Rail infrastructure, with Metro drivers able to see mainline tracks and signals. As of May 2015, signals using LED technology were installed only at the depot section. Metro drivers do not have benefit of the Automatic Warning System (AWS), or the Train Protection and Warning System (TPWS), available to mainline train drivers at the shared route. A fixed block command & control system is used in the T&W Metro. The Automatic Train Protection (ATP) system controls overspeeding and Signal Passed at Danger (SPaD) at certain locations only. The ATP system used is the Indusi system, which is a version of the German mainline railway warning and supervision system Induktives Sicherungssystem.

More information on the T&W Metro can be found in (29-31).

Methodology

This research uses a methodology based on a bivariate statistical analysis of historical incident data in the T&W Metro, combined with an observation and interview approach, to explore incident propagation and draw conclusions about the influence of design aspects, from the HF and PSF perspectives.

An in-depth examination of statistical trends allows for the uncovering of potential causal factors for driver-related incidents, with a focus on system design-related PSFs. Exploring correlations between different incident types has been chosen, to provide a better understanding of PSF inter-dependency, as well as the causal mechanisms of some incidents.

Input data

The raw data used in this research were provided by the Tyne & Wear Metro operator. 1282 incident reports from the 2011/12 and 2012/13 operating years were made available. Each operating year is divided into 13, four-week long periods, and Table 1 shows the dates for each period of 2012/13.

Table 1 Dates of the 13 operating periods of 2012/13

Period	1	2	3	4	5	6	7	8	9	10	11	12	13
Dates	1 Apr -29 Apr	30 Apr – 27 May	28 May – 24 Jun	25 Jun – 22 Jul	23 Jul – 19 Aug	20 Aug – 16 Sep	17 Sep – 14 Oct	15 Oct – 11 Nov	12 Nov – 9 Dec	10 Dec – 6 Jan	7 Jan – 3 Feb	4 Feb – 3 Mar	4 Mar – 31 Mar

The data are based on the entries contained in the incident reporting system. Each incident is logged with a description, date, time and location, as well as being allocated an incident type. Such incident types are grouped into larger categories, e.g. "technical domain incidents". The current reporting system is focused on operational incidents, especially technical faults. To perform the analysis, a new categorisation of the incident reports was required, as well as selecting the incident types to be retained. The categorisation, incident types used, and a brief description, are summarised in Table 2. The categorisation is focused on driver-related incidents, but some of the technical and operational domain incidents are also retained. Incident reports that did not fit any of the categories were excluded from the study. These included mainly incidents associated with pedestrians or vehicles trespassing at level crossings, which were assumed not to be associated with driver-related incidents.

Table 2. Categorisation of the incidents used in the study and their descriptions

Category	**Incident type**	**Description**
SPaD incidents	Category A SPaD	Category A Signal Passed at Danger (SPaD) occurs when a driver passes a signal displaying a stop aspect, without permission, and in error
	Other SPaDs	Occurs when a driver passes a signal displaying a stop aspect, without permission, due to a technical fault
Driver-related incidents	Overspeeding	A driver exceeding the maximum permitted speed of a line
	Failure to call	A driver skipping a scheduled stop, without permission
	Station overrun	Occurs when a train stops beyond the platform end
	Passenger entrapment	When a passenger is trapped by train doors
	Wrong side doors activation	A driver releases the wrong set of doors
	Wrong route	A driver sets an incorrect train description that later affects passenger information and route setting. It is also possible for the system to set points incorrectly. A driver who does not notice the issue, and takes the wrong route, is still at fault.
Technical domain incidents	Signal faults	Technical faults associated with signalling equipment
	Dispatch equipment faults	Faults of Driver Only Operation (DOO) equipment, e.g. platform mirrors and monitors
	Trainfault ATP	Technical faults of train-borne ATP equipment
	Trackfault ATP	Technical faults of lineside ATP equipment

Operational incidents	Doors obstruction	Passengers restricting train doors from closing
	Passenger overcarried	Passengers being left on a train when a train is taken out of passenger service
Interface incidents	LRA incidents	Low Rail Adhesion (LRA) conditions that did not lead to a more serious incident
	Foliage foul of infrastructure	Incidents associated with the metro infrastructure at risk because of foliage or vegetation

Three separate data sets based on time, period, and location were created, after assessing the raw data for consistency. This was required because incident causal mechanisms related to time, date and location usually fall into different PSFs groups. Time and date-related factors are associated with lighting and climatic conditions, patronage numbers and type, and seasonality. Furthermore, time-related factors also include individual driver factors, e.g. circadian rhythms. On the other hand, the location-related data set allows the study of the influence of system design features on metro driver performance, on specific parts of the network.

For the purpose of this paper, driver-related incidents are understood as a combination of different factors affecting a driver. Such a combination of factors, happening in a certain order, is capable of bypassing the safety mechanisms of a system.

Several incident types had a relatively small number of cases, e.g. station overrun, and failure to call incidents. Locations are understood as an approach station. Most of the driver-related incidents in this analysis are associated with station-based duties, thus approach station information is considered to be sufficient. All timeframes for the time-based data set are one hour long, e.g. 07:00:00 to 07:59:59, with the exception of 01:00:00 to 04:59:59, when only maintenance vehicles and trains operate on the system. The Metro's passenger flow has two peaks: between 7 and 9 am, and from 4 to 6 pm. To cope with increased passenger numbers, the number of trains in the network is at its highest during these peak hours.

The preliminary assessment of the data (32) confirmed the importance of the design-related factors in the data set. The assessment looked at the same data set only in terms of descriptive statistics, in order to obtain an overview of the Metro's performance. Consistency of distributions was checked only by plotting polynomial trend lines for each incident, for each operating year, making the results unreliable. Three incident peaks were discovered throughout the day, with the highest number of incidents occurring between 12 and 2 pm. This midday peak led to several hypotheses about the influence of certain passenger types at stations (the elderly, children) on incident propagation, with only a limited importance placed on the number of trains. Previous research suggests that the drastic change of environment at tunnel exit/entrance positively affects arousal levels (33), but the preliminary assessment did not find this to be the case for Metro drivers, thus it requires further investigation. These findings generated the need for the following additional indicators and data:

1. Information on schools and hospitals in a close proximity (500m) to a station was collected, to check how passenger types potentially influence incident propagation.
2. Data on the hourly number of trains were sourced from the operator, along with data on hourly driver sign-ons. Research from mainline railways suggests that train drivers have an increased risk of incident two hours after starting a shift, due to the presence of vibrations causing a decrease in arousal levels (33, 34).

Finally, research from the automotive industry indicates that a long exposure to monotonous physical environments decreases the arousal levels of car drivers (35). It was decided to check whether this applies to metro drivers, by correlating the distances between stations and the number of incidents.

Frequency distribution analysis

Using Microsoft Office 365 software, the frequency distribution of each incident type was studied, in order to identify peak times, seasonally inflated incident rates, and the worst performing locations. The current approach to incident analysis often focuses only on statistics from the entire network, whereas there is also a need to analyse local trends and risks (36). The four worst performing stations for certain driver-related incident types were selected, to carry-out in-depth examination of the potential factors inducing incident propagation at these specific locations. However, wrong route, and failure to call incidents (as defined in Table 2) were excluded from this analysis, due to:

- an insignificant number of 'failure to call' incidents;
- 'wrong route' incidents being constrained to certain stations used as terminuses in the Metro, due to the nature of the route setting tasks;

For category A SPaD incidents four years of data were available for the frequency distribution analysis. However, the bivariate correlation analysis (associations) is performed on 2011-13 data for this incident type

Bivariate correlation analysis

A bivariate correlation analysis was chosen to interrogate the data in order to:

- explore the existence of correlation between statistics, for two operating years, for each driver-related incident type, in order to check for consistency in year-on-year distribution;
- uncover potential associations between different incident types in all the data sets;

- explore possible associations between the additional data and driver-related incident types in the respective data sets.

Consistency in year-on-year distribution of a driver-related incident would suggest a clear-cut connection between the incident type and certain locations, times or periods. Associations found between the incident types indicate the potential presence of common causal factors. Exploring similarities in causal factors has the objective of enhancing understanding of the inter-dependency of PSFs in metro systems. It is important to note that a correlation found does not always suggest causation. In many cases the relationships will be spurious correlations, meaning that there are common factors affecting both variables.

The bivariate correlation analysis was carried out using IBM SPSS version 22. All variables (incident types) were checked for normality of distributions using either the Shapiro-Wilk, or Smirnov-Kalmogorov test, depending on sample size (37). If both variables were found to be normally distributed, the Pearson Product Moment Correlation (PPMC) was used as the preferred correlation method. If one of the variables was not normally distributed, then the Spearman Rank Correlation (SRC) technique was used.

Results

Under the proposed categorisation (table 2) more than 60% of the analysed incident reports were included in the sample for the bivariate statistical analyses. Year 2012/13 has approximately two times more incidents than 2011/12 but most of this increase is attributed to dispatch equipment faults which only started to be reported in 2012/13. When these faults are excluded, the increase is still significant with 43% more incidents in 2012/13. On the other hand, the increase in driver-related incidents is only 1.5%.

Consistency of driver-related incidents

Table 3 below shows the consistency in distribution of driver-related incidents over the two operating years. The three data sets are presented in different columns. Most of the driver-related incidents are localised to certain parts of the network. Only 2 out of 7 incident types are consistent in terms of timing of incidents. Category A SPaDs are the only driver-related incident type to show year-on-year correlation in the context of periods. However, as the correlation coefficient is negative, the distribution of this incident type is not consistent.

Table 3. Correlation of driver-related incidents, year-on-year. * correlation is significant at the 0.05 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed).

Incident type/Sample type	Date-based	Time-based	Location-based
Category A SPaDs	-0.565*	-0.123	0.283*
Overspeeding	-0.013	0.244	0.400**
Failure to call	0	0	0
Station overrun	0.459	0.221	0.281*
Passenger entrapment	-0.065	0.601**	0.353**
Wrong side doors activation	-0.012	0.427*	0.543**
Wrong route	-0.226	0.395	0.374**

Frequency distributions of driver-related incidents

Table 4 summarises the results for the driver-related incidents, in the T&W Metro. It displays an overview of the composition of the driver-related incidents in each year. For the two years under investigation, overspeeding and wrong side doors incidents were the most encountered types, with 26.3% and 26.6% of all incidents studied. The incidents associated with station procedures (wrong side doors activation, passenger entrapment) account for 46.6% of the entire data set.

In the context of seasonality, Category A SPaDs and overspeeding incidents occur most often at either the beginning or end of an operating year. Incident types known to demonstrate distinct seasonality, e.g. station overruns, were concentrated in the autumn periods. Finally, station-based incidents, including wrong route setting, tend to happen in the second half of an operating year. There are three possible incident peak times in the T&W Metro – around the morning and evening peak hours, and from 12-2 pm.

Table 4. Proportion of driver-related incidents by year and total.

Incident type	**2011/12**	**2012/13**	**For 2 years**
Category A SPaD	6.3%	10.4%	8.4%
Overspeeding	27.5%	25%	26.3%
Failure to call	2.8%	0%	1.2%
Station overrun	6.3%	4.8%	5.6%
Passenger entrapment	13.4%	26.4%	20.0%
Wrong side doors activation	36.7%	16.7%	26.6%

Wrong route	7.0%	16.7%	11.9%
Total	**100%**	**100%**	**100%**

Associations between incident types

In total, 60 associations were found between incident types. Half of these associations were found in the location-based data set, whereas the time-based and date-based samples had 11 and 19 associations, respectively. For time-based data, dispatch equipment faults account for 50% of the associations found. All of the associations have medium to high strength. In the date-based sample, Category A SPaDs have the highest number of associations (four), with one negative correlation between dispatch equipment faults and passenger over-carried incidents, and the majority of associations have medium to low strength. The majority of location-based associations are low in strength, with five significant negative correlation coefficients found, mostly with passenger entrapment incidents. Category A SPaD is involved in 20% of the correlations found in the location-based data set. Table 5 below provides an overview of the associations found for driver-related incidents only, together with summaries of the descriptive statistics for such incidents. The rationale behind the data summarised includes the following aspects:

- 'Failure to call' incidents happened at only three stations, between 2011 and 2013;
- Only three stations were selected for 'wrong route' incidents, as these stations account for 55.9% of all incidents of this type, with no other station having more than 6% of such incidents.

Table 5. Summary of the results. * correlation is significant at the 0.05 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed).

	Peaks		**Associations (correlation coefficient)**		
Incident type	**Peak period(s)**	**Peak time(s)**	**By period**	**By time**	**By location**
Category A SPaD	1-4, 12	4-5 pm; 8-10 am	None	Station overrun (.498*); Passenger entrapment (.574**); Wrong side doors (.601**); Trainfault ATP (.524*);	Overspeed (.256*); Wrong route (.334**); Signal faults (.269*); Trainfault ATP (.301*); Trackfault ATP (.260*); Passenger overcarried (.526**);
Overspeeding	1-3, 6, 8	12-5 pm	None	Passenger entrapment (.772*); Wrong side doors (.453*); Doors obstruction (.472*);	Category A SPaD (.256*); Trackfault ATP (.307*);
Failure to call	2, 7-9	1-2 pm	Trackfault ATP (.600*); Dispatch equipment (.566*);	None	Station overrun (.282*);
Station overrun	8-12	8-9 am; 11 am – 12 pm	Dispatch equipment (.666*); LRA (.718*);	Category A SPaD (.498*); Foliage fouls (.580**);	Failure to call (.282*); Passenger entrapment (.273*); Foliage fouls (-.407**);
Passenger	8-11, 13	12-3 pm; 4-5 pm	Doors obstruction (.578*); Dispatch equipment (.633*);	Category A SPaD (.574*); Overspeeding (.772**);	Station overrun (.273*); Doors obstruction (.280*);

entrapment				Wrong side doors (.696**); Doors obstruction (.606**)	Foliage fouls (-.377**); LRA (-.321*); Passenger overcarried (-.257*);
Wrong side doors	6, 8-9, 11, 13	1-3 pm; 7-10 am; 4-5 pm	None	Category A SPaDs (.601**); Overspeeding (.453*); Passenger entrapment (.696**); Foliage fouls (.606**);	Trackfault ATP (.285*);
Wrong route	6, 8, 10, 13	6-10 am; 5-8 pm	Dispatch equipment (.579*);	LRA (.450*); Passenger overcarried (.441*);	Category A SPaD (.334**); Signal faults (.293*) Foliage fouls (.398**); LRA (.261*); Passenger overcarried (.475**)

The four worst performing stations for selected driver-related incident types were studied in depth. The peak of the overspeeding at these locations is at the beginning of an operating year (April to June), and between midday and the evening peak. Majority of station overruns happen during late Autumn and Winter months, but such incidents are relatively evenly distributed throughout a day. There is a peak in passenger entrapment incidents around January, with an overall trend for such incidents starting from October onwards. In terms of times of a day, the 12-3 pm peak for passenger entrapments was discovered. Period 6 (Late August to mid-September) has the highest number of wrong side door activations, with the second half of an operating year (October onwards) having a higher frequency of such incidents. Finally, there are two relatively similar rises in wrong side door activations – around the morning peak, and between 1-3 pm.

Associations with additional indicators

Table 6 below displays the associations found between the additional data collected and driver-related incident types. Data on 'distance between stations' and 'schools and hospitals nearby' were analysed for correlations with driver-related incidents from the location-based data set. The remaining additional data was checked for associations with driver-related incidents from the time-based data set. The significance of the correlation coefficient was detected as similar to the previous section.

Table 6. Associations with additional data. * correlation is significant at the 0.05 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed).

	Distance between the stations	# hospitals and schools nearby	Number of trains in the network per hr	Number of drivers starting their shift per hr	Number of drivers who started their shift ~2 hrs before (per hr)
Category A SPaDs	0.017	0.008	0.632**	0.068	0.535*
Overspeeding	-0.119	-0.222	0.528*	0.304	0.435*
Overspeeding (4 worst performing)	N/A	N/A	0.408	0.292	0.274
Failure to call	-0.111	0.096	0.115	0.176	-0.031
Station overrun	0.094	-0.026	0.360	0.191	0.438*
Station overrun (4 worst performing)	N/A	N/A	0.168	0.016	0.240
Passenger entrapment	-0.224	0.086	0.594**	0.086	0.342
Passenger entrapment (4 worst performing)	N/A	N/A	0.330	-0.023	0.116
Wrong side doors activations	-0.213	-0.195	0.794**	0.224	0.580**
Wrong side doors activations (4 worst performing)	N/A	N/A	0.528*	0.247	0.414
Wrong route	0.167	0.166	0.130	0.012	0.491*

Discussion

The year on year increase in driver-related incidents is relatively small compared to 43% rise in overall number of incidents in the sample. Such rise in incident reporting without a considerable rise in driver-related incidents suggests improvements in the safety culture (38) as well as positive results from the Metro operator's effort to increase driver reporting rates. The changes in composition of driver-related incidents (table 4) allow tracking the operator's initiatives to address wrong-side door operation problem and reporting of passenger entrapments. On the other hand, it also shows lack of progress with category A SPaDs, overspeeding and wrong route incidents.

The composition of driver-related incidents on the Metro (Table 4) demonstrates that almost half happen while drivers are carrying out their station duties. This accounts for five times more incidents than category A SPaDs, despite a significant research focus on the latter incident type. Overspeeding accounts for a significant proportion of the incidents and requires in-depth analysis.

The consistency analysis (Table 3) confirmed the findings of the preliminary study, where the importance of location-based factors was discovered. Significant localisation to certain stations allows the study of each incident type and the drawing of hypotheses about elements of physical design contributing to driver performance there. The lack of year-on-year consistency for Category A SPaDs suggests the importance of individual driver factors. Better consistency was expected from the date-based sample, at least for station overrun and failure to call incidents, as those mostly happen during the low rail adhesion (LRA) season. Time-based factors are very variable, with many dependent on weather conditions, circadian rhythms of a driver etc. However, the consistency of station duty related incidents suggests the effects of patronage levels, crowding and the associated passenger disturbances.

Effects of approach distances, tunnel exits and time on duty

No associations were found between the approach distance and incident locations (table 6). As the longest approach time in the Metro is only two and a half minutes, it is possibly not long enough to induce boredom or to reduce driver vigilance. However, research from the automotive industry shows that sensory deprivation starts to appear rapidly in monotonous environments (35). It is hard to say what constitutes a monotonous environment for metro drivers, however it should not be very different from car drivers' outside environment in overground sections. Similarly, no associations were found with the number of schools and hospitals nearby (table 6), supporting previous research, by RSSB (39), that found no difference in driver detection of children, compared to adults. The 500m radius used may be not representative for elderly passengers, as 0.5 km is a long distance for mobility equipment users.

Exploring incident times, association with the number of of trains in the system occurs (table 6). Clearly, more trains cause more signals at danger and further risk of SPaDs. Moreover, additional services are provided to cope with peak demand and increased passenger levels which, as previously discussed, are important factors in incident propagation at stations. However, the central corridor (the busiest part of the network where two lines merge) has almost no driver-related incidents, proving the incidents are not caused simply by the number of trains. Hence it is safe to say that number of trains in the system only induces existing issues of driver performance, at the worst performing locations. It also means that focusing on the worst performing stations could bring substantial safety benefits. Associations with a driver's time on duty (table 6) suggests that 2 hours into the driving portion is a significantly riskier time than the start of a shift, which supports a claim of the overall monotonousness of the train driving task, in the Metro. Furthermore, it was discovered that locations associated with tunnel exits or entrances do not provide any additional increase in alertness or arousal levels. Twenty-four such locations were identified and explored, demonstrating 10% higher incident levels compared to the rest of the Metro network. This contradicts findings from mainline railways (33) and road, but can be explained by the specific skill and mind set requirement of metro drivers, as well as the comparative population size. This notion of the dip in performance, if incorporated into metro driver training and rostering, could bring significant safety benefits.

Metro infrastructure vs Network Rail infrastructure

The existence of the shared section between the Metro and NR allows for comparison of the infrastructure, using the incident statistics. First, the number of driver-related incidents on the NR infrastructure is 7.5% lower than on the Metro infrastructure. However, there are 75% fewer trains on part of the system, compared to the central corridor, thus supporting the conclusion that the number of trains is not a causal factor in incident propagation. Secondly, one particular Type 1 station demonstrated several station overruns outside of the LRA season. This station deviates from the standard Type 1 design somewhat, as the running signals are located considerably further from the platform edge than normal. It is possible that the Metro drivers use a running signal as a reference point when selecting stopping position. Thirdly, only 4.1% of the Category A SPaDs occurred at the NR infrastructure, where the NR four-aspect signals are used, even though this part of the Metro accounts for 12% of the stations and 19% of track-kilometres. It is possible to claim that the advance warning provided by four-aspect signalling has a positive effect on SPaD statistics. Furthermore, this part of the network has straighter approaches and better signal sighting distances, although it is more vulnerable to ‘see through’ SPaDs, where drivers focus on the more distant signal instead of the nearest signal down the line.

Locations deviating from standardised design

Despite a somewhat standardised Metro station design, many do deviate from the types presented in figure 1. The four worst performing stations for Category A SPaDs all have elements that do not fit any of the types. Three of those associate with sidings, turnaround facilities and subsequent use of ground position lights (GPL). Such locations are used for short peak services, when drivers are mostly pushed to maintain the timetable. However, most driver duties require them to enter the sidings, so it would be incorrect to blame lack of experience in using the GPL; it simply means that the design of this signalling type has serious flaws in terms of usability. Type 2 and Type 3 line terminus stations are also involved in several Category A SPaDs. Due to a layout that allows trains to arrive at either of the two platforms, the position of a running signal changes in relation to the driver's cab. Hence, situational awareness becomes as important as route knowledge at these stations. Interestingly some stations, where simplification of the standard design has occurred, demonstrate no incidents in the two operating years, e.g. one Type 1 station around the coast. That station fits Type 1 except for no running signals.

Three of the four worst performing stations for passenger entrapment are Type 3 underground stations. This design type features monitors and platform cameras for the DOO. Moreover, drivers only see approaching passengers when they enter a platform from a station atrium, thus losing situational awareness of events outside the platform. Moreover, passenger loading at such stations sometimes makes it hard to achieve a clear view of the doors, using the existing small monitors and only two platform cameras. Proximity to schools was deemed an important causal factor for incident levels at the only Type 1 worst performing station for this incident type, but this was not confirmed. However, passenger entrapments there happen during the colder Autumn-Winter months, hence bulkier clothing could be a causal factor. Furthermore, some drivers believe that passengers are more inclined to run for the doors after the warning tone, when it is cold, thus trapping themselves.

Even though wrong route incidents are mostly localised to terminus stations, some have happened at other locations, predominantly Type 1. All of those stations were used as turn-around points during engineering works, in the period under investigation. Moreover, period-based statistics supports this connection. It is possible to claim that the Metro drivers are struggling with procedures that are not part of their day-to-day driving, especially when using the stations from a different platform, or from the wrong direction.

Importance of platform side and speed limits

Tyne & Wear Metro includes stations of various types and there are parts of the network where, for example, a train departs a Type 1 station and arrives at a Type 2 or 3. This is where a platform side change occurs. It was expected that these locations would be hotspots for wrong side door activations, but the data demonstrate a more complex scene. Even though three out of the four worst performing stations are associated with platform change, more than 40% of such incidents happened at other stations. Moreover, the mean for wrong side door activations at non platform change locations is higher than at the expected locations. Interestingly, most of the wrong side door incidents at the worst performing station (Type 3 - 29% of all wrong side door activations in the Metro) happen travelling from the direction that does not involve platform side change. There was a 69% drop in such incidents between 2011/12 and 2012/13 at this location. This decrease happened after the backlight for an advertising board, situated next to a cab stopping position, was changed to a less bright one at that station. Furthermore, Type 2 and Type 3 line terminus stations have the same arrangement, with trains arriving at either of the two platforms, yet Type 2 station had no incident with the door release. It should however be noted that this particular Type 2 line terminus station is an overground station, whereas the Type 3 line terminus stations is located underground. The importance of lighting conditions is further suggested by the fact that 88.9% of Type 3 underground stations had at least one wrong side door activation. Finally, two stations deviating from the standard design (Type 1 and Type 2) had a high number of such incidents. These stations have running signals positioned on the other side of the track from normal. It is possible that drivers unconsciously select the set of doors to open, based on the position of a running signal, or ambient lighting conditions (platform side is always brighter at Type 3 stations).

All of the worst performing stations for overspeeding incidents have low speed limits in common. The speed limit through these locations is between 5 and 15 kmph. The line terminus station, with the highest number of incidents of this type, stands out for having a very steep drop, from 80 kmph to 5 kmph. It is possible to claim that drivers struggle to maintain a low speed limit for long distances, especially after driving at the maximum speed. This was also confirmed by informal conversations with some Metro drivers.

Associations

Associations between the incident types mostly revealed the expected connections. For example, overspeeding and Category A SPaDs are typically in the same locations, as often the same trackside equipment controls both train speed and moving authority. Supporting the suggestion of cognitive roots for SPaDs and wrong side door incidents (40), associations were found between these two types and the number of drivers 2 hours into the driving portion of their shift. Such associations prove common failure mechanisms and causal factors, for different incident types. It is important to note that the most associations were found in the location-based data sample, even though the coefficients were usually higher in other samples. This shows the inter-dependability of different incident types, in terms of design-related factors, but raises a question about whether those factors are really influential or whether there is simply more location-based factors involved in incident propagation.

Conclusions

The paper highlights the importance of design-related factors in the propagation of Metro incidents. Moreover, a high level of inter-dependence between causal mechanisms is shown, for location-based factors. High priority should be given to overspeeding and station-related incidents, as these constitute almost 70% of Metro driver-related incidents. Although the features of a metro system suggest superior route knowledge and increased familiarity of drivers with the system, the results show that this can lead to unsatisfactory safety performance, during non-routine operations, and at locations where situational awareness might be limited. Other locations that require increased attention are those stations that deviate from the standardised design. Several elements of the physical environment that are associated with such locations are ground position lights, hidden passenger approaches, change of platform side, imposed speed limits etc. On the other hand, simplification of the standardised design might also yield safety benefits. Infrastructure used by Network Rail shows fewer adverse effects on driver performance than the Metro's own infrastructure.

Drivers were found to lose their alertness and high performance levels approximately two hours into the driving portion of a shift. This finding, when used for rostering, could improve Metro's safety performance even further. Even though the number of trains passing through a station is not directly related to the number of incidents at that location, it can induce incident propagation in the problematic parts of the network. Environmental and personal factors should not be disregarded in further studies, especially for Category A SPaDs and passenger entrapments. Similarly, passenger loading shows an important contribution to incident causality.

List of abbreviations

HF(s)	Human Factor(s)
PSF(s)	Performance Shaping Factor(s)
SPaD	Signal Passed at Danger
RSSB	Rail Safety and Standards Board
ATP	Automatic Train Protection
AWS	Automatic Warning System
CCTV	Closed Circuit Television
PTI	Platform-Train Interface
DOO	Driver-Only Operation
LRA	Low Rail Adhesion
T&W	Tyne & Wear

Acknowledgements

The authors would like to thank DB Tyne & Wear Ltd., the operator of Tyne & Wear Metro, for the opportunity given to carry out this work and the access to the relevant data. This research is supported by the Institute for Sustainability at Newcastle University, through the Sir James Knott and Ridley PhD Scholarship.

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